



Research Article

<https://doi.org/10.1631/jzus.A2400522>



Preliminary study on evaluation indicators for urban engineering system sustainability

Junjie WU^{1,2}, Duanyang ZHUANG^{1,2✉}, Xuecheng BIAN^{1,2}, Yunmin CHEN^{1,2}

¹*Institute of Hypergravity Science and Technology, Zhejiang University, Hangzhou 310058, China*

²*MOE Key Laboratory of Soft Soils and Geoenvironmental Engineering, Zhejiang University, Hangzhou 310058, China*

Abstract: China's urbanization has entered a mid-to-late phase, and is characterized by high-density urban engineering projects that form systems coupled to geotechnical environments. These systems exhibit significant vulnerability due to strong spatiotemporal coupling, which hampers sustainable urban development. Traditional approaches to urban engineering design, construction, and maintenance tend to focus on individual projects and lack the ability to comprehensively evaluate system-level sustainability. Thus, with current methods, it is difficult to optimize the renewal and operation of high-density urban engineering systems. In this study, the constituent elements and key features of high-density urban engineering systems are discussed, and urban engineering system sustainability evaluation indicators are comprehensively reviewed. Viewed from perspectives of resilience, low-carbon development, and ecological impact, 66 performance indicators describing urban engineering systems are selected. The decision-making trial and evaluation laboratory (DEMATEL)-based analytic network process (DANP) method and the entropy weight method (EWM) are utilized to calculate these indicators' subjective and objective weights, respectively. Furthermore, the coupling relationships between evaluation indicators are explored, aiding the construction of an urban engineering sustainability evaluation index system. Finally, empirical analysis is conducted across six megacities in China (Tianjin, Hangzhou, Shanghai, Wuhan, Chongqing, and Shenzhen) to validate the effectiveness of the evaluation indicators. The findings reveal significant imbalances in the sustainability of urban engineering systems in China. Accordingly, potential strategies and indicators for targeted enhancement of these systems are discussed.

Key words: Urban engineering system; Geotechnical environment; Spatiotemporal coupling; Sustainability; Evaluation indicators

1 Introduction

By the end of 2022, China's urbanization rate had reached 65.2%, signaling a transition to the mid-to-late urbanization stage. Meanwhile, the population density of Chinese megacities significantly exceeds the global average (Hou et al., 2023), and rapid urbanization has driven the development of complex urban engineering systems. In these systems, surface structures, underground spaces, transportation networks, and energy facilities are intricately connected through geotechnical bodies and the environment. Such systems provide physical support for city operations, ensure proper functioning of urban activities, promote economic and social

development, and improve the environment in which humans live. However, the growing density of cities and aging infrastructure have created strong interdependencies and complex co-evolution phenomena among urban engineering projects. As a result, a failure or malfunction in one project can rapidly spread to interconnected projects and potentially the entire system, posing significant threats to the stability and sustainability of a city. For instance, in Zhengzhou, China, on July 20, 2021, there was an extreme rainfall which reached 201.9 mm/h. The local drainage system, which was designed for a once-in-50-year event, could only handle 32% of this rainfall rate. Consequently, the rainfall formed torrents that posed a danger to other urban engineering projects, leading to severe road damage, traffic disruptions, and catastrophic failures in underground spaces. The situation was also exacerbated by delayed emergency responses, imprecise measures, and a lack of unified command, ultimately resulting in 380

✉ Duanyang ZHUANG, zhuangdy@zju.edu.cn

Duanyang ZHUANG, <https://orcid.org/0000-0002-5431-0691>

Received Nov. 10, 2024; Revision accepted May 26, 2025;
Crosschecked Nov. 11, 2025; Online first Dec. 30, 2025

© Zhejiang University Press 2025

fatalities and direct economic losses amounting to 40.9 billion CNY (Zhang GR et al., 2022; Li et al., 2023). Similar incidents in other cities have highlighted the urgent need to address such systemic vulnerabilities.

Traditional urban engineering design, construction, and maintenance primarily focus on individual projects, thus neglecting urban engineering systems and lacking comprehensive system-level optimization. Therefore, the systemic urban vulnerability tends to increase, leading to issues such as disaster mismanagement, carbon emission imbalances, and pollution disorders. To specify, disaster mismanagement refers to the increased intensity and frequency that urban engineering projects are facing from natural and human-made disasters, making it difficult to prevent and mitigate the induced damage (McGlade et al., 2019). Carbon emission imbalances are characterized by environmental degradation in dense urban areas and aging districts, as a result of uncoordinated and excessive carbon emissions during construction, renovation, and maintenance projects (Chen X et al., 2020; Wang et al., 2022). Pollution disorders refer to increasingly complex and unmanageable pathways of pollution in high-density urban engineering projects, which result in a heightened risk of environmental deterioration (Tang et al., 2022).

To address the challenges above, it is imperative to promote sustainable construction and operation in the context of urban engineering systems. The aim is to meet contemporary urban functional needs without compromising the quality of life or resource demands of future generations, while meeting constraints of specific urban resources (Ding et al., 2016). By prioritizing sustainable development in urban engineering systems, impacts from potential disruptions can be mitigated, thereby enhancing long-term system performance. A comprehensive assessment of current research in the urban engineering system sustainability is fundamental to achieving these goals, as it would help identify critical engineering projects that require protection and enable improved allocation of limited resources across various subsystems. However, current research on urban sustainability assessment mainly focuses on economic, social, and ecological aspects, with few studies addressing sustainability assessment indicators for urban engineering systems (Sharifi, 2021). Moreover, since the factors influencing urban sustainability are multidimensional, it remains uncertain how factors interrelate and

which factors operate independently. Thus, there is an urgent need for multi-scale and multidimensional research to develop a system of sustainability assessment indices. This would help decision-makers monitor and evaluate the operational status of urban engineering systems, and provide metrics for policy-makers to evaluate strategies for enhancing sustainability.

This study focuses on the components and characteristics of high-density urban engineering systems that impact sustainable development. By reviewing current research on urban engineering system sustainability assessment, shortcomings in existing assessment frameworks are identified, and a novel configuration of sustainability assessment indicators for urban engineering systems is proposed. This is subsequently applied for empirical analysis of six Chinese megacities: Tianjin, Hangzhou, Shanghai, Wuhan, Chongqing, and Shenzhen. This application is performed to validate the proposed assessment methodology and provide recommendations for enhancing urban engineering system sustainability in these particular cities.

2 Overview of urban engineering systems

2.1 Components of urban engineering systems

Systems science categorizes systems into simple systems, simple giant systems, and complex giant systems based on the level of complexity, which includes the number and types of subsystems, the complexity of the relationships among subsystems, and structural differences (Qian et al., 1993). We posit that an urban engineering system is an open, complex, and giant system composed of multiple subsystems with specific functions. These subsystems interact continuously through the geotechnical environment, exchanging materials, energy, and information, and collectively forming the physical foundation of a city. Urban engineering systems can be divided into functional building system, underground space system, and infrastructure based on their constituent elements. Functional building system and underground space system provide space for human habitation and productive activities, while infrastructure supplies the necessary energy and materials for societal operations. Infrastructure can be further subdivided into six subsystems based on functional characteristics. These components are summarized in Table 1.

2.2 Characteristics of urban engineering systems

As an open complex giant system, the urban engineering system exhibits numerous characteristics, among which the most important are coupling, openness, and dynamicity. Various characteristics complicate evaluating the sustainability of these systems, necessitating the establishment of a comprehensive multilevel evaluation and management methodology. Since scientific evaluation methods are often the basis for decision-making and management, the current challenge is how to effectively assess the urban engineering system sustainability and provide guidance for efficient synergistic operation during renewal and maintenance of such systems.

2.2.1 Coupling

As cities become denser and more modernized, coupling relationships between the above components

have become increasingly complex (Fig. 1). The geotechnical environment leads to various urban engineering projects being tightly coupled and working synergistically at a physical level. Moreover, the couplings generated by functional coordination between different subsystems further expand the scope of impact, forming a large-scale spatiotemporal coupling mechanism (Li et al., 2022). When a single subsystem experiences a disturbance, such coupling mechanisms can amplify or generate new effects, creating a complex chain of cascading failures. This results in disturbances gradually spreading from smaller to larger urban areas, ultimately leading to significant vulnerabilities in terms of resilience, carbon emissions, and ecological impact.

From the perspective of resilience, increased coupling heightens the risk of complex emergencies. When a single aspect of an urban engineering system encounters a disaster or malfunction, the resulting functional failures often trigger cascading effects, causing

Table 1 Components of urban engineering systems

	Constituent element	Specific composition
Infrastructure	Energy facility system	Power supply system, heating system, etc.
	Water supply and drainage system	Water supply system, sewage system, etc.
	Communication system	Postal system, broadcast television system, etc.
	Disaster prevention and mitigation system	Fire protection system, emergency system, etc.
	Environmental facility system	Greening system, waste recycling system, etc.
	Transportation system	Road system, shipping system, etc.
Functional building system		Residential buildings, public buildings, etc.
Underground space system		Underground buildings, utility tunnels, etc.

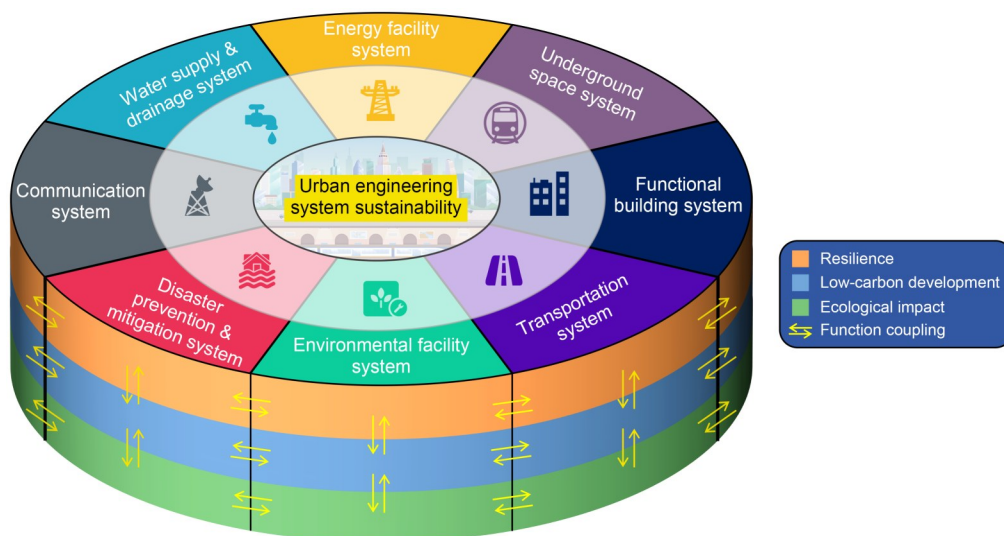


Fig. 1 Conceptual framework of urban engineering system sustainability. References to color refer to the online version of this figure

continuous propagation of losses that are difficult to predict (Ouyang, 2014). Both natural disasters (e.g., typhoons or earthquakes) and man-made disasters (e.g., terrorist attacks or industrial accidents) can trigger cascading failures. For example, when typhoon Hato landed in Macau, China, on August 23, 2017, the high proportion of land used for construction significantly increased the vulnerability of the local urban engineering system (Lin and Li, 2022). Therefore, the level-14 typhoon immediately caused seawater to backflow, leading to widespread flooding and power outages. The failures of the local drainage system and energy system quickly resulted in cascading collapses of communication and transportation facilities, causing underestimated human casualties and economic losses (Chow et al., 2019).

From the perspective of low-carbon development, varying construction times and lifecycles of individual projects, which are strongly coupled through the geotechnical environment, often complicate the understanding of performance evolution over the lifespan of dense urban engineering projects. This can significantly increase the difficulty of synergistic operation and maintenance of multi-stage urban projects. Currently, the service performance of densely constructed areas in China tends to be poor, and urban engineering carbon emissions account for a high proportion of total city carbon emissions. For instance, Shanghai's per capita CO₂ emissions (11.9 t) in 2019 were significantly higher than those of other major international cities such as London (9.6 t) and Tokyo (4.89 t) (Ji et al., 2023), with construction and transportation operations accounting for 25% of the total energy-related carbon emissions (Huang et al., 2019; Tian et al., 2024). This highlights the need for synergistic updates that promote energy conservation and carbon reduction.

From the perspective of ecological impact, coupling increases the vulnerability of the urban ecological environment. Failures in various urban engineering projects often lead to the spread of pollutants, resulting in complex pollution sources and emission pathways and ineffective regulation of urban groundwater and soil pollution. For example, since systemic effects were not properly considered in early urban planning, municipal pipelines are often shallowly buried and chaotically arranged. This can lead to sewage leaks during long-term service, causing uneven stress in nearby pipelines and chain leakage (Wang et al., 2021).

Statistics show that China's current sewage pipeline network has a chemical oxygen demand (COD) penetration rate of 66%, meaning over half of the pollutants enter the groundwater and soil through pipeline leaks (Cao et al., 2019).

Urban engineering systems also exhibit coupling relationships and feedback mechanisms across the above dimensions, with a failure in any dimension potentially triggering cascading failures in others. For example, if an urban engineering system is inadequately resilient to an earthquake, it could lead to leaks in pipelines, septic tanks, pumping stations, and wastewater treatment facilities (Wells et al., 2013), causing pollution and negatively affecting the system's ecological status.

2.2.2 Openness

The formation and evolution of urban engineering systems follow similar laws as living systems, where individual and group evolutions are achieved via constant material and energy exchange with the outside world (Shi et al., 2021). The operation and development of all subsystems are influenced by external factors, including climate conditions, natural environmental changes, international political and economic dynamics, national and regional policies and laws, population movements, cultural exchanges, and the flow of information. This openness necessitates that a single urban engineering system should effectively exchange and aggregate resources with other systems. For example, urban infrastructure must comply with international environmental agreements like the Paris Agreement on climate change, which requires cities to reduce greenhouse gas emissions and transition toward renewable energy sources (Kılıç, 2022); this might include upgrading the transportation system to promote public transit and cycling, retrofitting buildings for improved energy efficiency, and implementing sustainable waste management practices.

The openness of urban engineering systems introduces additional complexity into urban engineering design, construction, and maintenance. External factors may lead to profound and unpredictable impacts on system functionalities, thus requiring the system to be robust in all dimensions. Consequently, it is necessary to build a comprehensive evaluation system that can quantify how different factors may influence the system's sustainability.

2.2.3 Dynamicity

Urban engineering systems are constantly evolving in response to both internal developments and external changes. By undergoing continuous transformations influenced by technological advancements, policy shifts, environmental changes, and social dynamics, engineering projects may ultimately serve a different purpose from what was envisioned (Guma, 2022). The dynamicity of urban engineering systems adds complexity, necessitating top-level designs that are both scalable and adaptable. Scalability ensures that the system can adjust its capacity to meet changing demands, while adaptability allows it to modify functionalities to address new challenges. For example, the integration of renewable energy technologies into existing power grids necessitates systems that can accommodate variable inputs without compromising stability.

In order to effectively manage dynamicity, it is essential to develop a comprehensive evaluation system, which can monitor and evaluate the performance of urban engineering systems amidst continuous change. Such an evaluation system would enable governments to assess how well urban engineering systems are responding to growing or changing demands, and how their functionalities need to be modified to meet new challenges.

3 Research status on urban engineering system sustainability assessment

3.1 Origin of the urban sustainability concept

The concept of sustainable development first appeared in 1987 in the United Nations report entitled “Our Common Future” (WCED, 1987). It was defined as “the ability to meet the needs of the present without compromising the ability of future generations to meet their own needs” (Mebratu, 1998). This definition has since become a new reference point in environmental science research. The Earth Summit held in Rio de Janeiro, Brazil, in 1992 introduced 27 principles to guide global sustainable development, marking another milestone (Kori and Gondo, 2012). Since then, the concept of sustainable development has been incorporated into international treaties, national constitutions, and the laws of various countries (Luke, 2005; Redclift, 2005), serving as a conceptual framework for addressing issues in business (Amran et al., 2015), agriculture

(Zhang HR et al., 2022), industry (Mayyas et al., 2012), and urban development (Ahern, 2013).

In the 21st century, with the intensification of climate change and environmental issues, the concept of urban sustainability has evolved further. The United Nations General Assembly’s 2015 adoption of the “2030 Agenda for Sustainable Development” specifically calls for the creation of inclusive, safe, and disaster-resilient sustainable cities, introducing new ideas for urban development (Kumar et al., 2016). Subsequently, researchers have undertaken extensive work to investigate potential strategies that further this goal. This has included the widely adopted concept of urban resilience, which has been applied in areas such as disaster impact simulation, infrastructure risk assessment, and urban function loss prediction (Glaeser, 2022).

3.2 Research on urban engineering system performance evaluation

Currently, scholars have developed distinctive urban engineering performance evaluation systems based on different theoretical frameworks. Such evaluation systems can be analyzed from the following perspectives:

(1) From the perspective of evaluation objects, existing performance evaluation systems are primarily divided into two categories: evaluations of individual urban engineering subsystems and evaluations of interconnected urban engineering subsystems. The former focuses on examining specific subsystem performance indicators in detail, providing a basis for targeted improvements. For example, Mahmoud et al. (2022) utilized a generic sustainability rating tool within a multi-objective optimization model to evaluate and enhance surface building sustainability, focusing on life cycle cost and sustainability trade-offs. However, this type of evaluation tool overlooks the risk of cascading failures due to coupling between different subsystems, leading to the potential overestimation of subsystem performance and the creation of unsafe biases in engineering design and maintenance.

Evaluation systems that target interconnected urban engineering subsystems focus on the relationships among subsystems and evaluate the overall performance by analyzing failure risk evolution mechanisms. For instance, Wang et al. (2012) developed a framework to assess the vulnerability of power and water supply systems, and proposed system design strategies

based on multiple indicators. Although such an evaluation system does consider the coupling features between subsystems, it only covers certain types of engineering projects and overlooks the mediating role of the geotechnical environment. Additionally, due to the high cost of simulating complex coupling issues, some studies ignore implicit logical relationships between indicators and treat indicators as independent (Bi and Little, 2022).

(2) From the perspective of evaluation dimensions, existing evaluation systems explore multiple aspects, including resilience (Blagojević et al., 2023), carbon emissions (Yang PJ et al., 2022), ecology (Zhang HR et al., 2022), economics (Sun et al., 2017), and social impacts (Yang ZY et al., 2022). While these studies provide field-specific insights, they fail to comprehensively consider performance couplings and feedback mechanisms between different dimensions. This limits the precise enhancement of system functions and makes it challenging to achieve optimal renewal and maintenance of high-density urban engineering systems. Establishing systematic assessment dimensions is crucial for evaluating sustainability, as focusing on a single dimension may compromise sustainability in others.

(3) In terms of evaluation frameworks and methods, existing studies can primarily be divided into three types: The first type is based on qualitative analysis, utilizing expert opinions, case studies, and literature reviews to explore and understand various phenomena and trends within urban engineering systems, and to propose countermeasures. For example, Jiang and Tan (2022) analyzed 378 cases of underground infrastructure failures related to heavy rainfall, summarizing general features affected by drainage facility performance, climate conditions, and engineering geology. While such qualitative analysis does offer a deep understanding of research issues, it is highly subjective and difficult to verify as statistically significant.

The second type of evaluation system is based on quantitative analysis, which estimates objective variables through data and statistical methods (Shin et al., 2018). The main methods of this group include scenario analysis (Silva et al., 2018), model simulation (Leng et al., 2020), and system performance curves (Bao et al., 2020; Yang et al., 2021). Due to the spatial network characteristics of urban engineering systems, network-based modeling methods are commonly used in analyzing disaster damage and recovery progress.

For example, Zhang et al. (2018) proposed an evaluation framework for probabilistically predicting the functional loss of community buildings after earthquakes; the progression of urban building functionality failure was calculated by quantifying post-earthquake functional losses in the topology of water and electricity infrastructure. Also, Liu et al. (2020) calculated changes in greenhouse gas emissions before and after the implementation of green infrastructure, successfully assessing the contribution of green infrastructure to low-carbon urban drainage systems and the city overall. Quantitative analysis offers objective conclusions, but places higher demands on quantitative verification methods, which must be researched in greater depth.

The third type is based on semi-qualitative and semi-quantitative analysis, which mainly involves the use of indicator systems (Moslem et al., 2020). Because of the low empirical and technical requirements, this approach has been used to develop a range of self-service performance evaluation tools (Reed et al., 2009), such as the building research establishment environmental assessment method (BREEAM) (Umdu et al., 2021), and the population and demographics, environmental/ecosystem, organized governmental services, physical infrastructures, lifestyle and community competence, economic development, and social-cultural capital (PEOPLES) urban resilience evaluation system (Cimellaro et al., 2016). However, limitations arise from the strong subjectivities involved in indicator scoring and standard setting for such methods. Currently, there is no unified method for quantifying urban engineering system sustainability in terms of statistical indicators. Additionally, since existing evaluation frameworks have mainly been established in developed countries, some of these indicators fail to integrate with the setting in China.

Overall, research on the evaluation of urban engineering system sustainability is still in the exploratory stage. Although the existing evaluation systems enable performance assessment of certain subsystems based on different research backgrounds, there is still a lack of a comprehensive evaluation system covering various subsystems and different dimensions.

3.3 Validation of urban engineering system performance indicators

Limited by the complexity of urban engineering systems, traditional experimental methods under normal

gravity are insufficient for simulating performance evolution on the scale of a city (Chen YM et al., 2020). Additionally, due to the scarcity of real data on such performance changes, existing sustainability assessments of urban engineering systems have not been practically validated. Hypergravity physical simulation is a revolutionary engineering tool currently addressing these challenges, which can replicate the evolution of multiphase media over large scales and long durations; it operates under normal gravity in a laboratory scale, and within an observable time frame (van Loon et al., 2008; Chen et al., 2022).

Western countries have taken early initiatives to study hypergravity physical simulations of urban engineering system coupling mechanisms. In 1991, the U.S. Army Corps of Engineers built the world's largest capacity centrifuge (1200 $g \cdot t$) (g represents the gravitational acceleration) at that time (Ledbetter et al., 1991), which has been used to simulate the dynamic responses of geotechnical infrastructure under seismic or explosive conditions, as well as the long-term migration of contaminants in the environment. This centrifuge has successfully simulated the internal flooding disaster chain observed in New Orleans, Louisiana, during hurricane conditions (Ubilla et al., 2008; Blume et al., 2009). However, the current capacity of hypergravity centrifuges in China is insufficient, limiting the modeling of complex scenarios, intelligent renewal, and maintenance of urban engineering systems. There is thus an urgent need to develop similar large-scale spatiotemporal simulation devices.

4 Urban engineering system sustainability evaluation indicators

4.1 Selection of evaluation indicators

Since urban engineering system sustainability is a multidimensional issue, the most challenging task is the choice of evaluation indicators. To address this complexity, the indicators chosen in this study were rigorously screened through bibliometric analysis, which examined existing evaluation indices of different subsystems. Meanwhile, in order to incorporate the openness and dynamicity of urban engineering systems, the selected indicators were grounded in quantifiable and standardized statistical variables. This enables the capture of temporal variations in urban evolution while

ensuring applicability across cities of varying scales. Meanwhile, statistical variables with insufficient data were removed or replaced.

A set of typical indicators and their corresponding statistical variables are summarized in Section S1 of the electronic supplementary materials (ESM), and the attributes indicate whether the given variable enhances (+) or diminishes (-) the urban engineering system sustainability. The indicators were selected based on the subsystems defined in Section 2.1, and could be considered as a detailed description of different cities' resilience (32 indicators), low-carbon development (17 indicators), and ecological impact (17 indicators). Indicators in the resilience dimension were prioritized to quantify system robustness against disruptions, reflecting the capacity to maintain critical services during crises; indicators in the low-carbon development dimension were chosen to reflect sustainability transitions that align urban growth with emission reduction targets; indicators in the ecological impact dimension were selected to monitor environmental feedback to engineering operations.

4.2 Indicator weight calculation method

The evaluation indicators are weighted to signify their importance, with common weighting methods being divided into subjective and objective approaches. In this study, the subjective and objective weights were calculated by the decision-making trial and evaluation laboratory (DEMATEL)-based analytic network process (DANP) method and the entropy weight method (EWM), respectively. The integrated weights were then calculated using the maximizing deviation method (MDM). The calculation process of the evaluation indicator system is illustrated in Fig. 2.

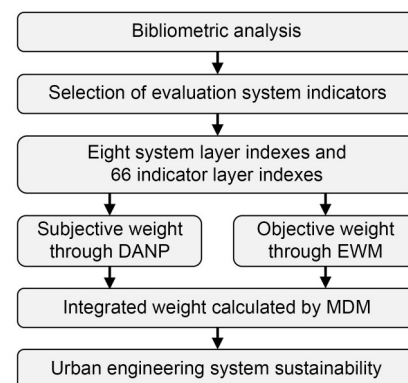


Fig. 2 Schematic flowchart of the methodology

4.2.1 Subjective weight calculated by the DANP

Subjective weighting plays a critical role in sustainability assessments, as it captures expert insights into systemic priorities and interdependencies. Traditional methods like analytic hierarchy process (AHP) assume unidirectional hierarchical relationships among criteria (Nefeslioglu et al., 2013), and fail to address feedback loops or bidirectional influences that are prevalent in complex urban engineering systems. Although the analytic network process (ANP) partially resolves this problem by accommodating network-like interactions, its reliance on pairwise comparisons alone often leads to oversimplified causal structures, as well as computational intractability in large-scale systems (Liu et al., 2022). Therefore, in order to express the coupling relationships among selected indicators, the DANP was employed to calculate the subjective weights. The DANP is a decision support tool that can reveal relationships and interdependence between various subjects, so as to facilitate problem-solving. By utilizing graph theory and matrix tools to quantify the direct and indirect relationships between indicators, the DANP can calculate the cause-and-effect relationship of each factor and convert the relationships among the factors into a structural model that enables visual representation of the interdependencies (Jiang et al., 2022). Referencing the research of Lin et al. (2022), five experts from the field of urban engineering construction were invited to participate in a survey that collected their assessments of the direct impact levels between evaluation indicators. The constructed evaluation system network hierarchy and the main steps of the DANP are described in Section S2 of the ESM.

4.2.2 Objective weight calculated by the EWM

Objective weighting is essential to counterbalance expert subjectivity and enhance the credibility of the evaluation system. To accurately differentiate evaluation objects and maximize the informational value of indicators, the EWM was used to determine the objective weights. Referencing the research of Luo et al. (2020), higher weights were assigned to indicators with greater data variability, with the goal of quantifying the uncertainty of each indicator.

4.2.3 Integrated weight calculated by the MDM

Combined weighting is critical for reconciling the strengths of expertise and data variability, ensuring a

balanced evaluation framework that mitigates the biases inherent in standalone methods. Therefore, the MDM was employed to optimize weight integration by maximizing the total deviation across evaluation objects. By formulating a constrained optimization problem to autonomously determine integration coefficients, this method preserves the causal nuances of DANP, while prioritizing entropy-driven disparities. The specific calculation steps can be referenced from Yi et al. (2019).

5 Empirical analysis

5.1 Selection of evaluation cities

A city cluster refers to a compact urban agglomeration centered around a megacity and includes at least three large cities or metropolitan areas connected by transportation and communication networks. Currently, China has five major city clusters: Beijing–Tianjin–Hebei, Yangtze River Delta, Middle Yangtze, Chengdu–Chongqing, and the Pearl River Delta (Tao et al., 2019). To comprehensively explore sustainability differences within China, six megacities from these clusters were selected to carry out an empirical analysis: Tianjin, Hangzhou, Shanghai, Wuhan, Chongqing, and Shenzhen.

It is worth noting that the urban engineering system sustainability discussed in this paper is limited to normal city operation scenarios, but the same methods could also be applied to analyze extreme disaster scenarios or other special circumstances.

5.2 Data sources and pre-processing

The data used for each indicator variable mainly came from the China City Statistical Yearbook, China Urban Construction Statistical Yearbook, China Energy Statistical Yearbook, China Statistical Yearbook on Environment, National Economic and Social Development Statistical Bulletin, the website of the National Bureau of Statistics, Statistics Yearbooks of selected prefectural cities, and official documents recognized by relevant governmental departments. The sample period was 2021, and missing data were filled in through linear interpolation of historical data.

To eliminate the differences in magnitude, size, and range between indicators, all data were scaled from 0 to 1 through normalization to ensure that different indicators can be compared straightforwardly.

5.3 Results and analysis

5.3.1 Calculation results of indicator weights

Taking power supply stability (A11) as an example to illustrate the calculation process of indicator weights, A11 obtained subjective and objective weights of 0.0194 and 0.0110 through the DANP and EWM, respectively, indicating that the integrated weight constraints range from 0.0110 to 0.0194. To maximize the variance of scores among evaluation objects while meeting the normalization constraint of all indicator weights, the calculated integrated weight for this indicator was 0.0194. Other indicator weights were similarly calculated, and the results are listed in Section S3 of the ESM.

5.3.2 Reliability validation

A reliability test of the evaluation system was conducted using the Cronbach’s alpha (α), which is a common means of assessing reliability. It works by comparing the amount of shared variance among the items making up an instrument to the amount of overall variance. α typically ranges from 0 to 1, with values closer to 1 indicating higher reliability of the evaluation results (Pinto et al., 2014). The overall α for the evaluation results is 0.8811, demonstrating that the constructed evaluation system reliably, consistently, and stably reflects the performance of each evaluation object regarding urban engineering system sustainability.

5.3.3 Evaluation results for different subsystems

Based on the established evaluation system and normalized data, the sustainability scores for each evaluation object were calculated. The ranking results for the overall system and the individual subsystems are shown in Fig. 3, and the explanation of evaluation systems A–H is listed in Section S1 of the ESM.

Shenzhen leads in five out of eight subsystems, exhibiting strong sustainability synergies. For instance, Shenzhen’s low-carbon public transport scale (F22) reduces reliance on fossil fuels and lowers energy intensity (A22). Meanwhile, Shanghai dominates the disaster prevention and mitigation system (D) and the functional building system (G). In contrast, Chongqing and Tianjin show weaker performance; the reasons for this can be attributed to: the coupling characteristics inevitably trigger cascading risks, the openness characteristic amplifies systemic vulnerability across different

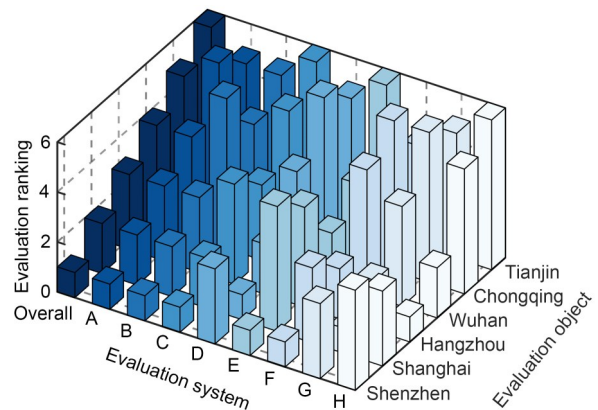


Fig. 3 Evaluation results ranking the different subsystems. References to color refer to the online version of this figure

regions, and the dynamicity characteristic increases uncertainty during system operations. For instance, Tianjin’s inefficient construction industry resource utilization (G21) intensifies the energy intensity (A22) and worsens air pollution control (E32); it also increases resource dependency on other cities.

5.3.4 Evaluation results across different dimensions

The normalized scores for each city across different dimensions are displayed in Fig. 4. The results reveal a significant disparity in overall evaluation scores: Shenzhen and Shanghai attain the highest scores (0.6343 and 0.6032, respectively), while Chongqing and Tianjin demonstrate lower performance (0.3399 and 0.3219, respectively). Notably, Shanghai’s top resilience score (0.3357) is directly attributed to its leading performance in the disaster prevention and mitigation system (D), since this means the city has strong adaptation to uncertainties from the dynamicity characteristic.

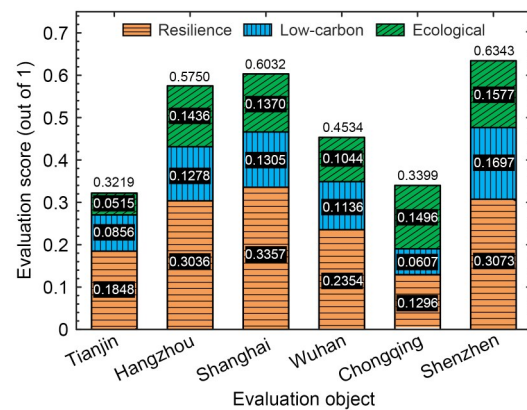


Fig. 4 Evaluation scores across different dimensions

Performance imbalance is also found across different dimensions within the same city. For example, Shanghai ranks second overall, but first in the resilience dimension, which is likely due to the different attention given to various dimensions during city policy formulation.

5.3.5 Enhancement measures and recommendations

As described in Section S3 of the ESM, the geological disaster forecast accuracy (D12) and mobile communication assurance (C13) are the most critical indicators affecting urban engineering system sustainability, with their integrated weights being 0.0264 and 0.0243, respectively. In contrast, the road traffic connectivity (F11) and internet transmission efficiency (C21) rank as the lowest indicators, with integrated weights of 0.0093 and 0.0087, respectively.

For specific cities, it is essential to analyze sustainability in different subsystems and dimensions of each urban engineering system. Taking Hangzhou as an example, its overall ranking among the selected cities is third, but its rankings across all subsystems are 3, 3, 4, 2, 4, 2, 2, and 1, respectively, indicating that Hangzhou currently places a high priority on the development of

the underground space system (H). However, improvements should be made in the sustainability of its communications system (C) and environmental facilities system (E); some of these improvements might include implementing stricter electromagnetic radiation management measures, enhancing broadband network assurance, and strengthening environmental protection efforts. Hangzhou’s ranking across different dimensions is uniformly third, indicating a balanced development across all dimensions.

As shown in Fig. 5, a comparative analysis between Hangzhou and Wuhan was conducted based on the scores of all indicators. There are notable differences in indicators between the selected cities: Hangzhou has significant advantages in pipeline network safety (B11), emergency resettlement (D13), green building development (G31), and underground space utilization (H21). On the other hand, Wuhan performs better in water supply stability (B12), internet transmission efficiency (C21), environmental risk management (E12), and construction industry efficiency (G11). Comparative analyses are beneficial for cities to learn from each other and avoid implementing “one size fits all” policies. For example, Hangzhou could learn

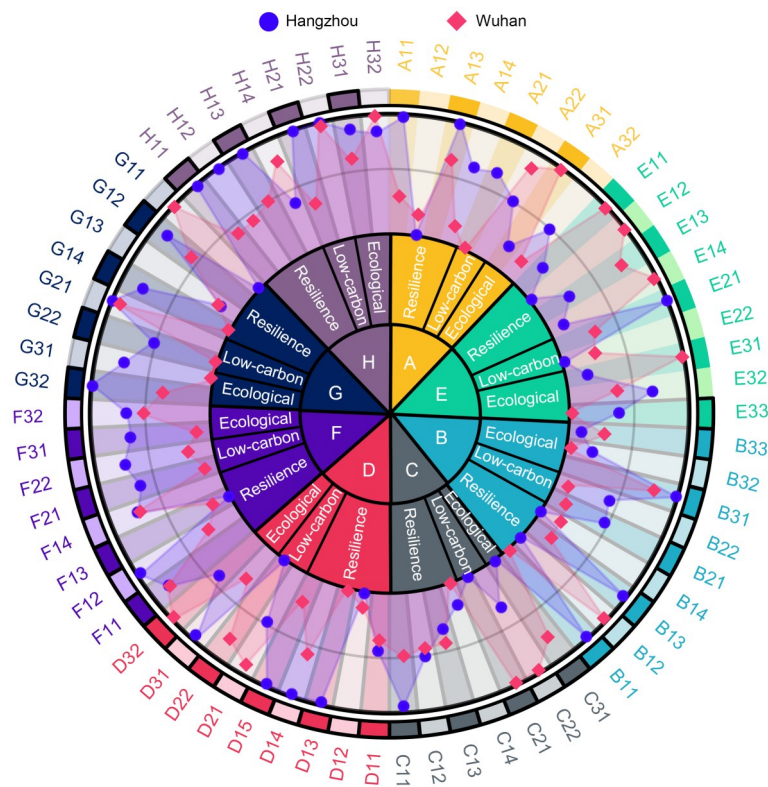


Fig. 5 Indicator scores of Hangzhou and Wuhan

from Wuhan’s expertise in pipeline network modernization and industrialized construction techniques in order to enhance water infrastructure resilience and resource efficiency, while synergizing these advancements with its own strengths in underground space utilization to improve urban sustainable development.

6 Discussion

6.1 Analysis of indicator coupling relationships

To further explore the interdependencies among the indicators, the influential relationships and causal effects of all indicators within each layer were calculated in the DANP method. The row sum vector \mathbf{d} (with elements d_i) and the column sum vector \mathbf{r} (with elements r_j) are derived from the total influence relation matrix, and the elements can be expressed by the following equations:

$$d_i = \sum_{j=1}^n t_{ij}, \quad i=1, 2, \dots, n, \quad (1)$$

$$r_j = \sum_{i=1}^n t_{ij}, \quad j=1, 2, \dots, n, \quad (2)$$

where t_{ij} is an element of the total-relation matrix and represents the total direct and indirect influence from indicator i to indicator j ; d_i measures the total influence exerted by indicator i on all indicators; r_j denotes the total influence received by indicator j from all indicators. The prominence values (d_i+r_j) are subsequently calculated to reveal the overall importance of each criterion in the system, while the relationship values (d_i-r_j) show the net causal effect. Positive relationship values indicate a “cause” indicator and negative values indicate an “effect” indicator.

However, it should be acknowledged that the interaction mechanisms among high-density urban engineering projects are complex. The DANP employed in this study provides a subjective simplification of these interactions, which may not capture all the intricacies of the real-world system.

6.1.1 System layer

Fig. 6 shows the influential network relation map created based on the prominence and relationship of each subsystem.

The results of the DANP reveal that the underground space system (H) has the highest prominence

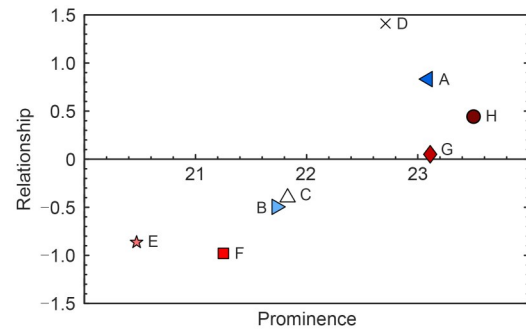


Fig. 6 System layer influential network relation map

value, indicating that efficient utilization of underground spaces can significantly promote the sustainable development of urban engineering systems. On the contrary, the environmental facility system (E) has the lowest prominence value, likely because impacts from failures in environmental facilities usually take a long time to become apparent.

Relationship values categorize indicators into cause-and-effect classes. The disaster prevention and mitigation system (D), which has the highest relationship value, exerts the strongest influence on other subsystems because it determines the city’s capabilities in disaster reduction, emergency response, and post-disaster reconstruction. Conversely, the transportation system (F), which has the lowest relationship value, shows the weakest impact on other indicators when disturbed, as it primarily responds to demands and changes in other subsystems.

6.1.2 Indicator layer

Similarly, an influential network relation map for the indicator layer index under conventional conditions is created, as illustrated in Section S4 of the ESM.

The prominence value for underground space planning (H12) is the highest, reflecting the role of underground spaces in alleviating urban land resource constraints. Conversely, the prominence value for traffic noise control (F31) is the lowest, possibly due to the complex causes of urban traffic noise and the lack of efficient measures to manage such noise.

Weather forecast accuracy (D11) has the highest relationship value and exerts the strongest impact on other indicators, mainly because of the increasing frequency of extreme weather events; this enhances the risk of unconventional emergencies such as power outages, transportation paralysis, and water shortages. The relationship value of the construction industry

efficiency (G11) is the lowest, which is consistent with its high dependency on providing construction resources to other subsystems.

6.2 Sensitivity analysis

The results of an evaluation system are generally related to different types of errors and uncertainties, including weighting criteria, data, knowledge of the system, and influential expert decisions (Foroozesh et al., 2022). Therefore, it is vital to assess the impact of uncertainty on the outcomes. To test the robustness of the established evaluation system, a sensitivity analysis using the one-at-a-time (OAT) method was conducted. The weight of a single indicator was modified by $\pm 10\%$ and $\pm 20\%$, while other indicators lost proportional shares to keep the weight sum unchanged. The sensitivity analysis results are displayed in Section S5 of the ESM.

The sensitivity analysis results indicate that the evaluation system exhibits different sensitivities to alterations of different indicator weights. The highest change rate is observed with changes in the weights of geological disaster forecast accuracy (D12) and heating security (A13), while the lowest change rate occurs with weight changes in mobile communication coverage (C12) and medical resource integration (D22). Despite these fluctuations in indicator weights, the relative rankings remained stable, confirming the system's robustness to weighting uncertainties.

6.3 Future research directions

While a systematic approach was employed in our proposed evaluation system for urban engineering system sustainability, it is important to acknowledge that the unavailability of certain statistical data, such as maximum load rate on the power grid, fire station density, and per-capita carbon emissions from transportation, has imposed limitations on this study. For instance, lacking information on fire station density hinders assessment of the city's preparedness and responsiveness to emergencies. Similarly, the absence of per-capita carbon emission data from transportation impedes the ability to accurately measure the environmental impact and effectiveness of policies aimed at reducing emissions. In order to address these data limitations, future research should prioritize the collection and integration of comprehensive datasets that encompass a broader range of sustainability indicators.

Collaborations with government agencies, urban planners, and utility companies could facilitate access to proprietary or difficult-to-obtain data.

Since this study only considered statistical data in 2021, future studies should also integrate multi-year data to explore how urban engineering system sustainability evolves. Longitudinal analyses could further investigate temporal feedback mechanisms, such as whether improvements in low-carbon public transport scale (F22) consistently reduce energy intensity (A22) or the effect eventually plateaus. Real-time data could also complement longitudinal investigations by revealing short-term anomalies and adaptive behaviors. Therefore, the development of advanced data collection technologies, such as internet of things (IoT) sensors and real-time monitoring systems, would not only resolve current data gaps but also empower predictive modelling that aids policy development.

7 Conclusions

China is presently facing greater vulnerabilities in urban engineering systems due to strong coupling in the geotechnical environments of densely populated areas. However, current urban engineering design, construction, and maintenance efforts primarily rely on technical specifications and standards developed for individual projects, which lack systematic evaluations of sustainability. This, in turn, poses challenges for renewal and maintenance work in high-density urban engineering systems. Focusing on the interconnected nature of high-density urban engineering systems, we systematically reviewed existing literature on urban engineering system performance evaluation indicators, selecting 66 indicators reflecting the performance of urban engineering systems across three dimensions: resilience, low-carbon development, and ecological impact. The methods of DANP and EWM are then used to calculate the subjective and objective weights of each indicator, respectively, and accordingly construct an urban engineering system sustainability evaluation index system. Furthermore, an empirical analysis of six Chinese megacities (Tianjin, Hangzhou, Shanghai, Wuhan, Chongqing, and Shenzhen) is conducted. The following findings were obtained:

(1) The proposed evaluation indicator system effectively quantified the sustainability of urban engineering

systems in each evaluated city. Notably, geological disaster forecast accuracy and mobile communication assurance were identified as the most critical indicators influencing urban engineering system sustainability.

(2) Significant imbalances were also observed in the comprehensive scores of the selected megacities. Shenzhen and Shanghai achieved the highest scores (0.6343 and 0.6032, respectively), while Chongqing and Tianjin had the lowest (0.3399 and 0.3219, respectively). Moreover, substantial variations in performance across different dimensions were observed within the same city, indicating intra-city disparities.

Acknowledgments

This work is supported by the Fundamental Research Funds for the Central Universities (No. 226-2024-00242), the Excellent Research Groups Project (No. 52588202), and the National Science Fund for Distinguished Young Scholars of China (No. 52125803).

Author contributions

Yunmin CHEN, Xuecheng BIAN, and Duanyang ZHUANG designed the research. Junjie WU and Duanyang ZHUANG processed the corresponding data. Junjie WU wrote the first draft of the manuscript. Duanyang ZHUANG helped to organize and revise the manuscript. Xuecheng BIAN revised and edited the final version.

Conflict of interest

Yunmin CHEN is the Editor-in-Chief of this journal, and is NOT involved in the editorial review or the decision to publish this article. Junjie WU, Duanyang ZHUANG, Xuecheng BIAN, and Yunmin CHEN declare that they have no conflict of interest.

References

- Ahern J, 2013. Urban landscape sustainability and resilience: the promise and challenges of integrating ecology with urban planning and design. *Landscape Ecology*, 28(6): 1203-1212.
<https://doi.org/10.1007/s10980-012-9799-z>
- Amran A, Ooi SK, Mydin RT, et al., 2015. The impact of business strategies on online sustainability disclosures. *Business Strategy and the Environment*, 24(6):551-564.
<https://doi.org/10.1002/bse.1837>
- Bao ML, Ding Y, Sang MS, et al., 2020. Modeling and evaluating nodal resilience of multi-energy systems under windstorms. *Applied Energy*, 270:115136.
<https://doi.org/10.1016/j.apenergy.2020.115136>
- Bi CY, Little JC, 2022. Integrated assessment across building and urban scales: a review and proposal for a more holistic, multi-scale, system-of-systems approach. *Sustainable Cities and Society*, 82:103915.
<https://doi.org/10.1016/j.scs.2022.103915>
- Blagojević N, Hefti F, Henken J, et al., 2023. Quantifying disaster resilience of a community with interdependent civil infrastructure systems. *Structure and Infrastructure Engineering*, 19(12):1696-1710.
<https://doi.org/10.1080/15732479.2022.2052912>
- Blume P, Burroughs G, Controls B, et al., 2009. Centrifuge DAQ system reinforces New Orleans levees. *EE: Evaluation Engineering*, 48(10):42-45.
- Cao YS, Tang JG, Henze M, et al., 2019. The leakage of sewer systems and the impact on the “black and odorous water bodies” and WWTPs in China. *Water Science and Technology*, 79(2):334-341.
<https://doi.org/10.2166/wst.2019.051>
- Chen X, Shuai CY, Wu Y, et al., 2020. Analysis on the carbon emission peaks of China’s industrial, building, transport, and agricultural sectors. *Science of the Total Environment*, 709:135768.
<https://doi.org/10.1016/j.scitotenv.2019.135768>
- Chen YM, Ma PC, Tang Y, 2020. Constitutive models and hypergravity physical simulation of soils. *Chinese Journal of Theoretical and Applied Mechanics*, 52(4):901-915 (in Chinese).
<https://doi.org/10.6052/0459-1879-20-059>
- Chen YM, Tang Y, Ling DS, et al., 2022. Hypergravity experiments on multiphase media evolution. *Science China Technological Sciences*, 65(12):2791-2808.
<https://doi.org/10.1007/s11431-022-2125-x>
- Chow ECH, Wen M, Li L, et al., 2019. Assessment of the environmental and societal impacts of the category-3 typhoon Hato. *Atmosphere*, 10(6):296.
<https://doi.org/10.3390/atmos10060296>
- Cimellaro GP, Renschler C, Reinhorn AM, et al., 2016. PEOPLES: a framework for evaluating resilience. *Journal of Structural Engineering*, 142(10):04016063.
[https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0001514](https://doi.org/10.1061/(ASCE)ST.1943-541X.0001514)
- Ding L, Shao ZF, Zhang HC, et al., 2016. A comprehensive evaluation of urban sustainable development in China based on the TOPSIS-entropy method. *Sustainability*, 8(8):746.
<https://doi.org/10.3390/su8080746>
- Foroozesh F, Monavari SM, Salmanmahiny A, et al., 2022. Assessment of sustainable urban development based on a hybrid decision-making approach: group fuzzy BWM, AHP, and TOPSIS–GIS. *Sustainable Cities and Society*, 76:103402.
<https://doi.org/10.1016/j.scs.2021.103402>
- Glaeser EL, 2022. Urban resilience. *Urban Studies*, 59(1):3-35.
<https://doi.org/10.1177/00420980211052230>
- Guma PK, 2022. The temporal incompleteness of infrastructure and the urban. *Journal of Urban Technology*, 29(1): 59-67.
<https://doi.org/10.1080/10630732.2021.2004068>
- Hou YL, Kuang WH, Dou YY, 2023. Observing the compact trend of urban expansion patterns in global 33 megacities during 2000–2020. *Journal of Geographical Sciences*, 33(12):2359-2376.
<https://doi.org/10.1007/s11442-023-2180-0>
- Huang BJ, Chen YX, McDowall W, et al., 2019. Embodied

- GHG emissions of building materials in Shanghai. *Journal of Cleaner Production*, 210:777-785.
<https://doi.org/10.1016/j.jclepro.2018.11.030>
- Ji LQ, Xin J, Zhao CC, 2023. Energy consumption and carbon emissions: measurement and analysis—the case of Shanghai in China. *Waste and Biomass Valorization*, 14(1): 365-375.
<https://doi.org/10.1007/s12649-022-01876-w>
- Jiang HB, Lin YX, Luo X, et al., 2022. Understanding the selection of cross-border import e-commerce platforms through the DANP and TOPSIS techniques: a multi-study analysis. *Journal of Global Information Technology Management*, 25(1):26-53.
<https://doi.org/10.1080/1097198X.2021.2022397>
- Jiang WZ, Tan Y, 2022. Overview on failures of urban underground infrastructures in complex geological conditions due to heavy rainfall in China during 1994–2018. *Sustainable Cities and Society*, 76:103509.
<https://doi.org/10.1016/j.scs.2021.103509>
- Kılıç Ş, 2022. Urban emissions and land use efficiency scenarios towards effective climate mitigation in urban systems. *Renewable and Sustainable Energy Reviews*, 167: 112733.
<https://doi.org/10.1016/j.rser.2022.112733>
- Kori E, Gondo T, 2012. Environmental sustainability: reality, fantasy or fallacy. The 2nd International Conference on Environment and BioScience, p.105-109.
<https://doi.org/10.7763/IPCBE.2012.V44.22>
- Kumar S, Kumar N, Vivekadhish S, 2016. Millennium development goals (MDGs) to sustainable development goals (SDGs): addressing unfinished agenda and strengthening sustainable development and partnership. *Indian Journal of Community Medicine*, 41(1):1-4.
<https://doi.org/10.4103/0970-0218.170955>
- Ledbetter RH, Hughes SA, Rollings MP, et al., 1991. Large Centrifuge: a Critical Army Capability for the Future. Miscellaneous Paper GL-91-12, Department of the ARMY, Washington, USA.
- Leng LY, Mao XH, Jia HF, et al., 2020. Performance assessment of coupled green–grey–blue systems for Sponge City construction. *Science of the Total Environment*, 728:138608.
<https://doi.org/10.1016/j.scitotenv.2020.138608>
- Li N, Wang F, Magoua JJ, et al., 2022. Interdependent effects of critical infrastructure systems under different types of disruptions. *International Journal of Disaster Risk Reduction*, 81:103266.
<https://doi.org/10.1016/j.ijdrr.2022.103266>
- Li Y, Ye SS, Wu QZ, et al., 2023. Analysis and countermeasures of the “7.20” flood in Zhengzhou. *Journal of Asian Architecture and Building Engineering*, 22(6):3782-3798.
<https://doi.org/10.1080/13467581.2023.2208195>
- Lin SH, Zhang HJ, Li JH, et al., 2022. Evaluating smart office buildings from a sustainability perspective: a model of hybrid multi-attribute decision-making. *Technology in Society*, 68:101824.
<https://doi.org/10.1016/j.techsoc.2021.101824>
- Lin Y, Li HX, 2022. An analysis of urban vacant land on the Macau Peninsula. *Journal of Geographical Research*, 5(3): 13-21.
<https://doi.org/10.30564/jgr.v5i3.4595>
- Liu BS, Yang ZQ, Xue B, et al., 2022. Formalizing an integrated metric system measuring performance of urban sustainability: evidence from China. *Sustainable Cities and Society*, 79:103702.
<https://doi.org/10.1016/j.scs.2022.103702>
- Liu JH, Wang J, Ding XY, et al., 2020. Assessing the mitigation of greenhouse gas emissions from a green infrastructure-based urban drainage system. *Applied Energy*, 278:115686.
<https://doi.org/10.1016/j.apenergy.2020.115686>
- Luke TW, 2005. Neither sustainable nor development: reconsidering sustainability in development. *Sustainable Development*, 13(4):228-238.
<https://doi.org/10.1002/sd.284>
- Luo J, Chen SY, Sun X, et al., 2020. Analysis of city centrality based on entropy weight TOPSIS and population mobility: a case study of cities in the Yangtze River Economic Belt. *Journal of Geographical Sciences*, 30(4):515-534.
<https://doi.org/10.1007/s11442-020-1740-9>
- Mahmoud S, Hussein M, Zayed T, et al., 2022. Multiobjective optimization model for the life cycle cost-sustainability trade-off problem of building upgrading using a generic sustainability assessment tool. *Journal of Construction Engineering and Management*, 148(7):04022050.
[https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0002281](https://doi.org/10.1061/(ASCE)CO.1943-7862.0002281)
- Mayyas A, Qattawi A, Omar M, et al., 2012. Design for sustainability in automotive industry: a comprehensive review. *Renewable and Sustainable Energy Reviews*, 16(4):1845-1862.
<https://doi.org/10.1016/j.rser.2012.01.012>
- UNDRR (United Nations Office for Disaster Risk Reduction), 2019. Global Assessment Report on Disaster Risk Reduction 2019. UNDRR, Geneva, Switzerland.
- Mebratu D, 1998. Sustainability and sustainable development: historical and conceptual review. *Environmental Impact Assessment Review*, 18(6):493-520.
[https://doi.org/10.1016/S0195-9255\(98\)00019-5](https://doi.org/10.1016/S0195-9255(98)00019-5)
- Moslem S, Alkharabsheh A, Ismael K, et al., 2020. An integrated decision support model for evaluating public transport quality. *Applied Sciences*, 10(12):4158.
<https://doi.org/10.3390/app10124158>
- Nefeslioglu HA, Sezer EA, Gokceoglu C, et al., 2013. A modified analytical hierarchy process (M-AHP) approach for decision support systems in natural hazard assessments. *Computers & Geosciences*, 59:1-8.
<https://doi.org/10.1016/j.cageo.2013.05.010>
- Ouyang M, 2014. Review on modeling and simulation of interdependent critical infrastructure systems. *Reliability Engineering & System Safety*, 121:43-60.
<https://doi.org/10.1016/j.res.2013.06.040>
- Pinto FST, Fogliatto FS, Qannari EM, 2014. A method for panelists’ consistency assessment in sensory evaluations based on the Cronbach’s alpha coefficient. *Food Quality and Preference*, 32:41-47.
<https://doi.org/10.1016/j.foodqual.2013.06.006>
- Qian XS, Yu JY, Dai RW, 1993. A new discipline of science—the study of open complex giant system and its methodology. *Journal of Systems Engineering and Electronics*, 4(2):2-12
- Redclift M, 2005. Sustainable development (1987–2005): an oxymoron comes of age. *Sustainable Development*, 13(4):

- 212-227.
<https://doi.org/10.1002/sd.281>
- Reed R, Bilos A, Wilkinson S, et al., 2009. International comparison of sustainable rating tools. *Journal of Sustainable Real Estate*, 1(1):1-22.
<https://doi.org/10.1080/10835547.2009.12091787>
- Sharifi A, 2021. Urban sustainability assessment: an overview and bibliometric analysis. *Ecological Indicators*, 121:107102.
<https://doi.org/10.1016/j.ecolind.2020.107102>
- Shi YJ, Zhai GF, Xu LH, et al., 2021. Assessment methods of urban system resilience: from the perspective of complex adaptive system theory. *Cities*, 112:103141.
<https://doi.org/10.1016/j.cities.2021.103141>
- Shin S, Lee S, Judi DR, et al., 2018. A systematic review of quantitative resilience measures for water infrastructure systems. *Water*, 10(2):164.
<https://doi.org/10.3390/w10020164>
- Silva M, Leal V, Oliveira V, et al., 2018. A scenario-based approach for assessing the energy performance of urban development pathways. *Sustainable Cities and Society*, 40:372-382.
<https://doi.org/10.1016/j.scs.2018.01.028>
- Sun X, Liu XS, Li F, et al., 2017. Comprehensive evaluation of different scale cities' sustainable development for economy, society, and ecological infrastructure in China. *Journal of Cleaner Production*, 163:S329-S337.
<https://doi.org/10.1016/j.jclepro.2015.09.002>
- Tang WZ, Pei YS, Zheng H, et al., 2022. Twenty years of China's water pollution control: experiences and challenges. *Chemosphere*, 295:133875.
<https://doi.org/10.1016/j.chemosphere.2022.133875>
- Tao Y, Li F, Crittenden J, et al., 2019. Measuring urban environmental sustainability performance in China: a multi-scale comparison among different cities, urban clusters, and geographic regions. *Cities*, 94:200-210.
<https://doi.org/10.1016/j.cities.2019.06.014>
- Tian YF, Zuo SD, Ju JH, et al., 2024. Local carbon emission zone construction in the highly urbanized regions: application of residential and transport CO₂ emissions in Shanghai, China. *Building and Environment*, 247:111007.
<https://doi.org/10.1016/j.buildenv.2023.111007>
- Ubilla J, Abdoun T, Sasanakul I, et al., 2008. New Orleans levee system performance during hurricane Katrina: London Avenue and Orleans Canal South. *Journal of Geotechnical and Geoenvironmental Engineering*, 134(5):668-680.
[https://doi.org/10.1061/\(ASCE\)1090-0241\(2008\)134:5\(668\)](https://doi.org/10.1061/(ASCE)1090-0241(2008)134:5(668))
- Umdu DÇ, Alakavuk E, Koyuncu A, 2021. BREEAM communities: criteria aim, status, strengths and weaknesses. International Conference on Digital Age & Technological Advances for Sustainable Development (ICDATA), p.208-215.
<https://doi.org/10.1109/ICDATA52997.2021.00048>
- van Loon JJWA, Krausse J, Cunha H, et al., 2008. The large diameter centrifuge, LDC, for life and physical sciences and technology. Proceedings of the "Life in Space for Life on Earth Symposium", p.92.1-92.2.
- Wang J, Liu GH, Wang JY, et al., 2021. Current status, existent problems, and coping strategy of urban drainage pipeline network in China. *Environmental Science and Pollution Research*, 28(32):43035-43049.
<https://doi.org/10.1007/s11356-021-14802-9>
- Wang SL, Hong L, Chen XG, 2012. Vulnerability analysis of interdependent infrastructure systems: a methodological framework. *Physica A: Statistical Mechanics and its Applications*, 391(11):3323-3335.
<https://doi.org/10.1016/j.physa.2011.12.043>
- Wang XC, Yang L, Wang YT, et al., 2022. Imbalances in virtual energy transfer network of China and carbon emissions neutrality implications. *Energy*, 254:124304.
<https://doi.org/10.1016/j.energy.2022.124304>
- WCED (World Commission on Environment and Development), 1987. Our Common Future. Oxford University Press, Oxford, UK.
- Wells NS, Clough TJ, Condron LM, et al., 2013. Biogeochemistry and community ecology in a spring-fed urban river following a major earthquake. *Environmental Pollution*, 182:190-200.
<https://doi.org/10.1016/j.envpol.2013.07.017>
- Yang PJ, Peng S, Benani N, et al., 2022. An integrated evaluation on China's provincial carbon peak and carbon neutrality. *Journal of Cleaner Production*, 377:134497.
<https://doi.org/10.1016/j.jclepro.2022.134497>
- Yang YY, Li J, Huang Q, et al., 2021. Performance assessment of sponge city infrastructure on stormwater outflows using isochrone and SWMM models. *Journal of Hydrology*, 597:126151.
<https://doi.org/10.1016/j.jhydrol.2021.126151>
- Yang ZY, Clemente MF, Laffrèchine K, et al., 2022. Resilience of social-infrastructure systems: functional interdependencies analysis. *Sustainability*, 14(2):606.
<https://doi.org/10.3390/su14020606>
- Yi PT, Dong QK, Li WW, 2019. Evaluation of city sustainability using the deviation maximization method. *Sustainable Cities and Society*, 50:101529.
<https://doi.org/10.1016/j.scs.2019.101529>
- Zhang GR, Feng W, Lei Y, et al., 2022. Generation and evolution mechanism of systemic risk (SR) induced by extreme precipitation in Chinese urban system: a case study of Zhengzhou "7 20" incident. *International Journal of Disaster Risk Reduction*, 83:103401.
<https://doi.org/10.1016/j.ijdrr.2022.103401>
- Zhang HR, Zhang JW, Song JF, 2022. Analysis of the threshold effect of agricultural industrial agglomeration and industrial structure upgrading on sustainable agricultural development in China. *Journal of Cleaner Production*, 341:130818.
<https://doi.org/10.1016/j.jclepro.2022.130818>
- Zhang WL, Lin PH, Wang NY, et al., 2018. Probabilistic prediction of postdisaster functionality loss of community building portfolios considering utility disruptions. *Journal of Structural Engineering*, 144(4):04018015.
[https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0001984](https://doi.org/10.1061/(ASCE)ST.1943-541X.0001984)

Electronic supplementary materials

Sections S1–S5